Son 2/PCT

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
17 January 2002 (17.01.2002)

PCT

(10) International Publication Number
WO 02/04975 A1

(51) International Patent Classification[7]: G01S 1/24, 3/02

(21) International Application Number: PCT/US01/20066

(22) International Filing Date: 21 June 2001 (21.06.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/612,334 6 July 2000 (06.07.2000) US

(71) Applicant: SIRF TECHNOLOGY INC [US/US]; 148 E. Brokaw Road, San Jose, CA 95112 (US).

(72) Inventor: BRODIE, Keith, J.; 12 Silveroak, Irvine, CA 95129 (US).

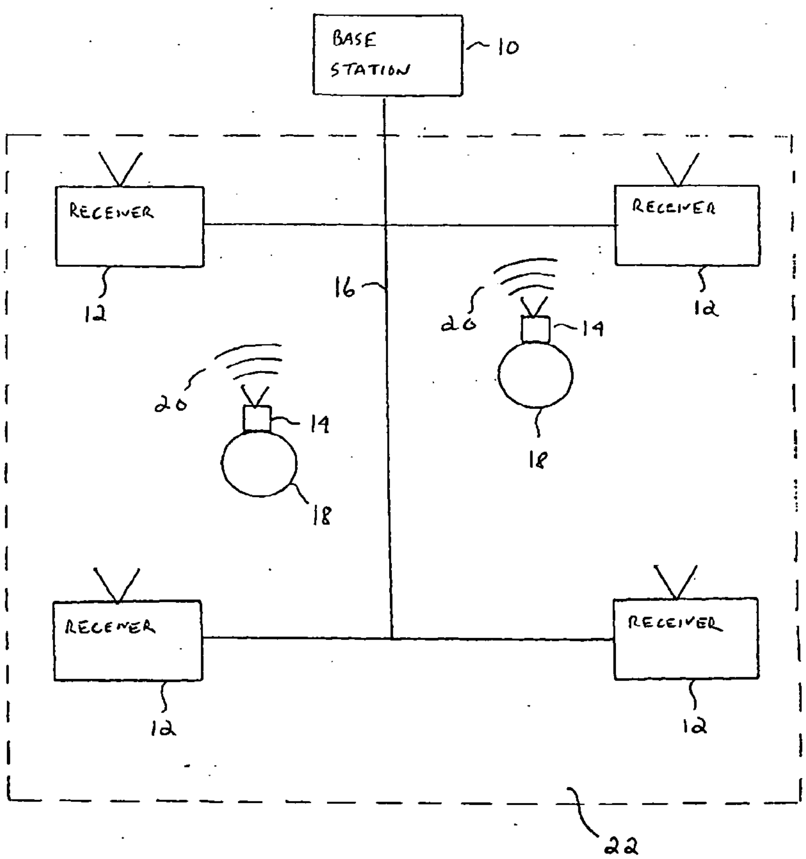
(74) Agents: SARISKI, David, S et al.; Fulwider Patton Lee & Utech LLP, Howard Hughes Center, 6060 Center Drive, Tenth Floor, Los Angeles, CA 90045 (US).

(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: LOCAL AREA BEACON SYSTEM FOR POSITION DETERMINATION



(57) Abstract: A plurality of beacon signal receivers (12) are positioned to define a local area (22). Objects (18) within the local area (22) are equipped with beacons (14) which transmit beacon signals (20) at random times, preferably over the same carrier frequency. The beacon signal (20) comprises a beacon code burst comprising a family code and a beacon-identification code. The receivers (12) receive the beacon signals (20), decode the beacon-identification code and record the time of arrival of each beacon signal with a local clock. A base station (10) receives data indicative of the beacon-identification code and time of arrival and processes the difference in the time of arrival of beacon signal (20) at each of the receivers (12) to determine the location of the beacon (18) within the local area (22) and the identification of the object (18) from which the beacon was transmitted.

WO 02/04975 A1

Published:
— *with international search report*

LOCAL AREA BEACON SYSTEM FOR POSITION DETERMINATION

BACKGROUND OF THE INVENTION

Field of the Invention:

The invention relates generally to position determination of objects within a local area and more particularly to a system for and a method of determining the location of objects within a locally defined area using a beacon system.

Description of Related Art:

It is often desirable to maintain location information on objects within a local area. Such local areas may be either indoor, outdoor or a combination of both. For example, in an airport there are large ground service fleets comprising mobile vehicles, cargo trailers, stairs, mobile service elevators, etc. that are moving throughout the airport region. Objects comprising the ground service fleet occasionally collide with each other and with aircraft moving to and from gates. Obviously, these are expensive and dangerous mishaps. Another exemplary situation in which location information on moving objects is highly desirable is a burning building with a group of firefighters inside of it. If a firefighter is lost in the smoke and debris, he may be impossible to locate. If the scene commander has a picture of all of the firefighter's locations he can optimize their deployment to protect their lives and save victims and property.

An obvious solution to this problem is the use of the Global Positioning System (GPS) as a location determination tool. Such a system, however, may be cost prohibitive in certain situations wherein hundreds of objects are within a local area. In other situations, such as the previously described indoor firefighting situation, the use of the GPS may precluded due to signal blockage.

Hence, those concerned with knowing the location of objects within a local area have recognized a need for a cost effective location determination system that operates independent of the GPS. This invention fulfills those needs and other.

SUMMARY OF THE INVENTION

In a first aspect, the present invention relates to a system for determining the location of a plurality of objects within a local area. In its most basic form, the system includes, for each object, a beacon carried by the object for transmitting a beacon signal at a random time. The basic system further includes at least three receivers located within the local areas for receiving each beacon signal and recording the time of arrival of each beacon signal with a local clock. The system also includes a base station for receiving data indicative of the time of arrival and processing the difference in the time of arrival of the beacon signal at each of the receivers to determine the location of the beacon within the local area.

In a detailed facet of the invention, each beacon transmits its beacon signal over the same carrier frequency. In a further detailed aspect, multiple beacon signals are carried over the same carrier frequency through the use of at least one of time-division multiplexing and code-division multiplexing. In a still further aspect each receiver separates the multiple beacon signals by at least one of time-division multiplexing and code-division multiplexing.

In another detailed facet of the invention the beacon signal comprises a beacon code burst comprising a family code and a beacon-identification code. In a further detailed aspect the family code is added to the beacon signal by phase shift keying. In yet another further aspect, each receiver correlates a replica of the family code with the family code of the received beacon signal to detect the arrival of a beacon signal.

In a second aspect, the invention relates to a method of determining the location of the plurality of objects within a local area. The method includes the steps of transmitting a beacon signal at a random time from each object within the local area. The method also includes the step of receiving each beacon signal at at least three receivers located within the local areas and at each receiver, recording the time of arrival of each beacon signal with a local clock. The method further includes the step of processing the difference in the time of arrival of the beacon signal at each of the receivers to determine the location of the beacon within the local area.

In a detailed aspect of the invention, each receiver comprises a GPS receiver and the method further comprises the step of synchronizing the receiver local clocks by transferring GPS time to the local clocks. In another detailed facet of the invention, each receiver

comprises a GPS receiver and the method further comprises the step of synchronizing the receiver local clocks using differential GPS processing with a common set of corrections. In yet another detailed aspect, the method further includes the step of synchronizing the receiver local clocks using send and reply correction messages from a master clock to observe and compute the delay time between the master clock and the receiver.

These and other aspects and advantages of the invention will become apparent from the following detailed description and the accompanying drawings, which illustrate by way of example, the features of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a block diagram of a local area beacon system (LABS) for tracking objects within a local area;

FIG. 2 is a block diagram of a LABS as applied within a local area wherein the tracking of ground vehicles and aircraft is desired;

FIG. 3 is block diagram of an exemplary beacon for use in the LABS of FIGS. 1 and 2;

FIG. 4 is block diagram of an exemplary receiver for use in the LABS of FIGS. 1 and 2;

FIG. 5 is grid depicting the locations of five LABS receivers within a local area;

FIG. 6 is a graph showing the horizontal dilution of precision (HDOP) of ground vehicles relative to the LABS receivers of FIG. 5;

FIG. 7 is a graph showing the horizontal dilution of precision (HDOP) of aircraft relative to the LABS receivers of FIG. 5 and

FIG. 8 is a graph showing transmission collision probability of a LABS as a function of code rate.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, wherein like reference numerals denote like or corresponding parts throughout the drawing figures, and particularly to FIG. 1, there is shown a local area beacons system (LABS), comprising a base station 10, three or more receivers 12 and one or more beacons 14, each mounted to a mobile object 18, the

movement of which is to be tracked. The base station 10 is connected to each receiver 12 with a data cable 16. Each beacon 14 is a low cost, low power, transmit-only, radio-frequency device which supports precise determination of the location of the mobile object 18 on within a local area 22. In a one configuration of the LABS, the local area 22 is approximately twenty-five square kilometers, but could possibly range from the size of a building or room up to a few hundred square kilometers or more.

Each beacon 14 transmits a beacon signal 20, the composition of which is described in detail below. The beacon signals 20 are received by the set of receivers 12 in and around the local area 22. In order to effectively determine the location of a beacon 14, there must be at least three receivers 12 within the local area 22 and may be more. Additional receivers 12 improve the location determination geometry and minimize the effects of any blockage in the local area 22..

Each receiver 12 records the time-of-arrival (TOA) of inbound beacon signals 20 with a precise local clock which is synchronized with each of the other local clocks. The local clocks may be synchronized by several methods. In one embodiment, each receiver 12 contains a global positioning system (GPS) receiver which is used to transfer GPS time to the local clock. In a second embodiment each receiver 12 uses differential GPS (DGPS) processing with a common set of corrections supplied over the data cable 16 from the base station 10. In another embodiment, a single master clock at the base station 10 synchronizes all of the receiver clocks using send-and-reply correction messages to observe and compute the delay time on each data cable 16 between the base station 14 and the receiver 12.

Position determination is carried out by processing the difference in time-of–arrival of the beacon signal 20 at each of the receivers 12. This time difference of arrival (TDOA) processing removes any common clock uncertainty from the measurements. Specifically, the time of transmission of the beacon signal 20 is not known by the receivers 12 because the beacons 14 transmit at random times. The TDOA between receivers 12 is independent of the time of beacon signal 20 transmission. The TDOA depends on the relative location of the receivers 12 and the beacon 14.

The use of randomized transmission times and code-division multiplexing allows multiple beacons 14 to operate on a single carrier frequency in the local area 22. During typical LABS operation a multitude of beacons 14 transmit code bursts at random intervals. These code bursts include a unique beacon-identification (ID) codes which identifies the item 18 from which the beacon 14 is transmitting. The code burst further includes a family code which, in a preferred embodiment, is shared by each beacon 14. Each beacon's 14 unique ID code is combined with the family code in an exclusive-or operation. The receivers 12 use multiple digital channels to correlate with the beacon family code, determine the time-of-arrival, and decode the unique beacon ID code to identify the object.

With reference to FIG. 2, in an exemplary application, the LABS operates within an airport 28, wherein the locations of both ground vehicles 24 and aircraft 26 are tracked. In this particular application five receivers 12 positioned around an airport 28 receive simultaneous transmissions from beacons 14 attached to ground vehicles 24 and aircraft 26. The output of the LABS is a set of vehicle ID's with current positions and speeds. In this application of the LABS the beacon 14 positions and speeds are transmitted over a standard communications landline 32 from the LABS base station 10 to a ground traffic control station 30. In another application, the base station 10 itself may contain an integral display or be attached to a display to see the beacon 14 locations. The LABS base station 10 is also connected by landlines 34 to the LABS receivers 12. The messages from the receivers 12 to the base station 10 include the received signal ID, the received signal time-of-arrival referenced to the common clock, and signal quality indicators for beacon transmissions received.

The remaining links 36 shown in FIG. 2, which are not annotated, are the RF signals broadcast by the beacons 14 and picked up by the receivers 12. Transmissions are shown for a ground vehicle 24 and a taxiing aircraft 26. These transmissions are one-way. Another set of RF links (not shown), applicable to receivers 12 equipped with GPS receivers, are the GPS signals tracked at the receivers 12 for their disciplined local clocks. In this configuration, the base station 10 includes a DGPS portion which provides messages to the receivers 12 including correlator pre-positioning information for enhanced

beacon signal acquisitions, a selected GPS constellation to transfer time to the receiver clock or DGPS corrections for use by the LABS receiver's GPS receiver element.

Each beacon 14 is a transmit-only device, and its operation is not synchronized with other beacons or the base station 10. As previously mentioned, each beacon 14 transmits a code burst at randomized intervals. The receivers 12 separate multiple transmissions by time-division and code-division multiplexing, through successive attempts to synchronize with the family code portion of the code burst. Destructive collisions occur when two beacons 14 transmit the family code within one chip period of each other. The code rate and repetition interval can be varied to support any desired number of beacons 14 in the local area 28 with a specified probability of collision. In one implementation, a 3.6 MHz code rate supports 1000 beacons with one hertz transmissions with a probability of collision less than 10^{-3}. The consequence of a collision is that a single position report is missed for each of the beacons 14 involved. Randomization of the transmission interval in each beacon 14 ensures that two beacons cannot "lock-up" and send repeated colliding transmissions.

The family code is a binary sequence that is added to the carrier in the beacon 14 with phase shift keying. The simplest alternative is binary phase-shift keying (BPSK). More complicated phase shift keying alternatives are possible. Any m-ary PSK signal can be used, where m is an arbitrary integer greater than one. Typical m-ary PSK modulation schemes include binary (m=2) and quadrature (m=4). The m-ary PSK signal is the basis for the precise determination of the TOA of the beacon signal at each receiver 12. Each receiver 12 has one or more digital channels that correlate a replica of the family code with received signals to detect the arrival of a beacon signal.

In one embodiment of the invention, a vehicle equipped with a beacon 14 transmits a 10 millisecond BPSK spread spectrum code burst in the 915 MHz band approximately once a second. This code burst is received, time-tagged, and decoded for its unique ID number by each receiver 12. Each receivers 12 sends a message with this data to the base station 10. The base station 10 matches up the ID's of signal messages from all the receivers 12. Reasonableness checks are performed on signal strength, angle of arrival and TDOA to eliminate multipath and strong interference. The surviving measurements are

processed to update the track of the beacon 14 and hence the track of the vehicle 24, 26 to which the beacon is attached. The updated track information is passed along to the ground traffic controller 30.

In the airport application, the LABS can be extended such that aircraft 26 already equipped with DGPS receivers can utilize the LABS as an RF modem to transmit their position to the ground traffic controller 30. In this case the position information is combined with the family code as well as the beacon's unique ID code. Aircraft that are not DGPS equipped can be equipped with a LABS beacon 14 at a much lower cost to provide their position to the ground traffic center 30. Aircraft-mounted beacons 14 can be activated at preset altitude or by the gear down signal. Once activated, the aircraft are tracked and their positions integrated with those of the ground service fleet for display.

In an alternate configuration, a different family code may be used for objects of different types. For example, aircraft 26 and ground vehicles 24 may have different family codes. Code-division multiplexing is used to separate the families in the receivers 12.

With reference to FIG. 3, in a preferred embodiment, a LABS beacon 14 consists of a battery pack 38, a single chip microcontroller 40, a crystal oscillator 42, a frequency synthesizer 44, a mixer 52, a bandpass filer 53, a BPSK modulator 46, an RF amplifier 48, and an antenna 50 mounted in a container of some sort. A beacon 14 need be no larger than a pager. The standard vehicle beacon 14 has an eight centimeter vertical antenna 50, a quarter-wave monopole for the 915 MHz band. Beacons 14 can be directly connected to the vehicles power system. In some applications a battery-powered beacon which is not vulnerable to shorts or spikes on the vehicle's power system is preferred. Vehicles which have lost power may be the most crucial to locate.

Each beacon 14 transmits a pseudorandom bit sequence, *i. e.* a code burst, and then goes to sleep for a variable delay, typically one second. The bit sequence is BPSK modulated onto the carrier. The delay between transmissions is randomized so two beacons cannot get synchronized and continuously jam each other out. In one configuration, the baseline transmission time is ten milliseconds. A 3.6 MHz spreading code is used to modulate the carrier throughout the transmission. The beacon 14 uses 256 code bits per data bit and can transmit more than 100 bits of data over the link in a single

code burst. A beacon 14 does not have exclusive use of the frequency when it is transmitting. Multiple beacons 14 use code division multiplexing to share the channel. The preferred embodiment is to use a single linear maximal sequence (LMS) for all the beacons 14 with the individual beacon's unique ID number encoded on the LMS sequence by an exclusive-or operation of the ID bits with a segment of the code. The LMS code provides the lowest cross-correlation possible for a given code length. The LMS n-bit sequence has the lowest auto-correlation of any n-bit sequence with a phase shifted replica of itself assuming the correlation function is accumulated over the entire sequence length. The receivers 12 can track the same LMS sequence from multiple beacons 14 because they are not starting the sequence at the same time. Thus the receiver 12 is continuously attempting to acquire and track a single LMS sequence with multiple digital channels. A "low battery alarm" bit can be encoded with the ID for self-powered beacons.

In another embodiment, data encoding can be more complex than direct exclusive-or of the ID bit with a code segment. The data can be m-ary encoded on the spreading code. M-ary encoding provides some advantage in bit error rate (BER) for a given energy/bit to noise density ration (E_b/N_0) at the cost of receiver complexity. With m-ary encoding the receiver 12 must perform decision directed carrier recovery versus a simple Costas loop for exclusive-or encoding.

A typical RF link budget for the invention is shown below. The budget in Table 1 shows a 10 dB margin for 100 milliwatt transmit power over a five kilometer link, sufficient for airports.

Beacon Transmit Power	20.00 dBm	100.00 mW
Beacon Antenna VSWR Loss (2 to 1)	0.51 dB	
Beacon Antenna Gain	0.00 dBi	
Path Loss (5 km, 915 Mhz)	106.00 dB	
Receiver Antenna Gain	0.00 dBi	
Receive Antenna VSWR Loss (2 to 1)	0.51 dB	
Receiver Input Power	-87.02 dBm	9.97 uV (50 Ohm)
Receiver Sync Threshold (GRE GINA +3db)	-97.00 dBm	
Link Margin	9.98 dB	

The beacons 14 can be directly wired into a vehicle power system, but the bulk of the beacons 14 are battery powered and can be used on any vehicle. This embodiment of the invention supports one year of continuous operation off a single battery pack. This keeps the logistical burden down. An estimate of the mission requirements is summarized in Table 2.

Beacon Output Power	100	mW
Transmission Time	10	ms
Transmit Energy	1000	erg
Transmitter Efficiency	50	%
Battery Energy	2000	erg
Standby Power	10	uW
Standby Time	990	ms
Standby Energy	99	erg
Average Beacon Power Usage	2.0099	mW
Baseline Battery Pack Capacity 2 LiMn02 'C' Cells - 4.5 AmpHr (Panasonic, Ultralife, Sanyo...)	20250	mW Hr
Battery Pack Life	10075	Hr
	420	Day

With reference to FIG. 4, each receiver 12 includes one or more antennas 54. Associate with each antenna 54 is a RF hardware channel 56. In a preferred embodiment each receiver 12 includes a single omni-directional antenna 54, but multiple element antennas with beam-forming capability may be used.

The receiver 12 may be one of several different architectures, direct conversion, single conversion, double, or triple conversion. The resultant filtered IF or RF signals are sampled and digitized by a bandpass filter 58, RF amp 60, mixer 62 and digitizer 64 prior to being presented to the multiple digital hardware channels 56. They may be directly down-converted in frequency or they may be sub-sampled to achieve down-conversion. The digitized signals are then searched for correlation peaks and tracked in the fashion of a GPS receiver or direct sequence spread-spectrum modem.

The receivers 12 use precise clocks to time tag the inbound m-ary PSK messages from the beacons 14. The act of successfully correlating the receiver's code replica with the inbound beacon signal determines the time of arrival of the beacon's signal in receiver clock time. The fundamental accuracy limits are the code phase measurement error and the clock error. The limiting factor for the code phase error is the effective bandwidth of the beacon signal. The definition of the effective bandwidth and the computation of the range error limit for the sin(x)/x spectrum can be found in Skolnik, Introduction to Radar Systems, McGraw-Hill, 1980, pp. 405. Assuming the BPSK signal is filtered at the first null, the range error limit is

$$\delta R = 0.336\left(\frac{E}{N_0}\right)^{-1/2} \textit{ where}$$

δR is the range error divided by the chip length and

$\frac{E}{N_0}$ is the energy per symbol divided by the noise density.

One embodiment of the invention uses 3.6 MHz chip rate BPSK. The RF link budget, shown earlier, gives the receiver front end input power at the five kilometer range as –87.02 dBm for a 915MHz 100 milliwatt transmitter. Using a noise figure of 10 dB for

the receiver front end, a figure easily surpassed by off the shelf ISM band receiver chips (for example, the RF Microdevices RF2908 915 MHz spread spectrum receiver chip has a noise figure of 3.5 dB) the range error limit is a function of the symbol integration time, or the number of code bits per data bit. We can use this relationship to establish the minimum number of chips per symbol, where in this case a symbol is a single data bit. This relationship has been used to compute that 250 chips per symbol are sufficient to drive the TOA error limit below one meter. At 250 chips per symbol the 3.6 MHz code rate of the LABS is capable of transmitting 14.4 kilobits per second or 144 bits in the nominal 10 millisecond transmission.

In another embodiment of the invention the integration time is increased beyond the symbol time through the use of decision-directed carrier recovery. This is a trade-off of increased receiver complexity and computational burden to obtain a better energy to noise density ratio and lower range error.

Some fundamental problems addressed by the LABS are the near-far problem and multipath. The near-far problem is common to mobile communications systems. For beacons 14 with equal power, the beacon closest to the receiver 12 tends to overwhelm the signals from beacons further away from the receiver, effectively setting the receiver automatic gain control (AGC) and receiver A/D converter. The LABS limits this problem through time division multiplexing. The beacon 14 transmits randomized bursts, so that a beacon 14 very close to a receiver 12 cannot block out other beacon signals repeatedly. While collisions and missed bursts are expected from the beacons 14, continuously missed bursts from a individual beacon are not expected.

The next level of defense against the near-far problem is the selection of low cross-correlation codes. If code cross-correlations are kept below 33 dB, for example, then 30 dB power difference between the near and far beacons should not prevent the acquisition of the far beacon's signal. This does imply a wide dynamic range in the receiver A/D, at least 6 bits to support 30 dB of dynamic range with an ideal AGC. If the receivers 12 are positioned such that no beacon 14 can get closer than 100m, then 33 dB of isolation allow the acquisition of signals throughout a 100m to 3 km range without the receiver being swamped by the near beacon signal.

In another embodiment of the invention multiple-element antennas are used at the receiver 12 and beam forming techniques are used to isolate signals along different lines-of-sight.

Multipath may be categorized into several regions based on the delay of the reflected ray relative to the primary ray. In "close multipath", multipath rays arrive at the receiver 12 within one code chip interval of the primary ray. This can be treated by increasing the chip rate and/or by increasing the front-end bandwidth to estimate the effects of multipath on the observed correlation peak. Typically an attempt is made to correlate two or more code replicas, to best fit the multipath distorted correlation peak.

In "distant multipath", multipath rays arrive at the receiver 12 more than one code chip interval from the primary ray. This is generally screened off by the selection of a code with low autocorrelation. It is critical that the receiver 12 detect the first ray when measuring TOA, not the strongest ray, which may not be the direct ray.

In "total multipath", multipath rays may be the only received signal if the direct ray is completely blocked. In this case no direct TOA measurement is formed. Instead, the multipath ray is detected so it can be thrown out of the measurement set. The receiving antenna systems are sighted to minimize the amount of blockage from fixed features in the region of interest, but moving aircraft and ground service vehicles create a dynamic blockage environment. The use of multiple receivers 12 to track the same signal is advantageous in this situation. The time of arrival and angle of arrival at each receiver 12 as well as prior vehicle location information can be combined to develop a reasonableness test for the detection of multipath signals.

Each LABS receiver 12 collects digitized samples. For ten megahertz, ten bit sampling with five receivers 12 there is a total of 500 megabit per second of data collected. In one embodiment, optimal processing is conducted at the base station 10 by collecting all the data and matching the received code sequences from each receiver antenna. While this is possible, the preferred embodiment is to perform the correlations at each receiver 12. Each receiver 12 outputs a TOA, a C/N_0 estimate, and an ID for each beacon message 20 received. The TOA is determined by a digital correlator operating on the samples collected at that location. Multiple digital correlator channels operate off of the same

sampled RF data stream. The base station 10 uses the differenced TOAs, and C/N_0 to perform reasonableness checks and discard multipath rays. The remaining differenced TOAs are processed to update the beacon's 14 position.

The preferred embodiment of TOA processing in the base station 10 is to difference TOA's from the receivers 12 and present the TDOA measurements to an extended Kalman filter (EKF) to update the estimated beacon position and velocity. The beacon states in the EKF may include the speed and heading, so the beacon's 14 position can be predicted for short intervals. The predicted beacon may be used to preposition correlators in the receivers 12 to minimize acquisition time. Alternatively direct solution of the time-difference equations can be used. This places the location of the beacon on the intersection of two or more hyperbola branches. Each hyperbola branch is the set of points that result in a range difference between two receivers 12 sufficient to cause the observed TDOA. This inverted Loran processing, in the Loran chain the mobile element determines which hyperbolas it is on by observing the time differences of received pulses from the synchronized transmitters in the Loran chain. The calculations are the same, however in LABS they are carried out at the base station 10, the beacon 14 has no knowledge of its own position.

The geometry of the receiver positioned around the local area controls the dilution of precision (DOP) of the system. DOP is a convenient way to express the effects of geometry on the fix accuracy. DOP relates the one sigma position error to the one sigma measurement error. FIG. 5 is a plot of the location of five receiver 12 for a hypothetical airport local area contained within a 3 kilometer square region. Four of the receiver sites 12 are 141 meters off the corners of the square while a fifth receiver 12 is on top of a control tower. Each receiver 12 location is indicated with a box and annotated with the elevation of the antenna in meters.

There are two classes of beacons 14, those affixed to ground vehicles 24 (FIG. 2) and those affixed to aircraft 26. Each beacon class utilizes separate spreading codes and the LABS receivers 12 and base station 10 know which type of beacon signal 20 they are receiving. The information is used to determine which type of solution to compute. For the ground vehicles, the elevation is known. The solution sought is therefore two-

dimensional. The horizontal dilution of precision (HDOP) for the ground vehicles can be computed as a function of their position within the three kilometer airport region. This is shown in FIG. 6. This can be mapped to expected position error by multiplying the HDOP by the expected TOA accuracy of 1.5 meter two sigma. The expected horizontal position error in meters is 1.5 times the HDOP value given in the contour. The entire airport region can be covered with two meter, two sigma, horizontal accuracy for ground vehicles.

For the most accurate horizontal solution, the airport's ground elevation data must be imported into the base station 10. In addition, the height above ground for each vehicle that a beacon 14 is installed on should be entered as well. However, the receiver 12 array has low observability of the vertical channel, and missing elevation data will not seriously degrade horizontal accuracy.

For aircraft with beacons 14 the system allows for the possibility that the aircraft is not yet taxiing, but is still in the air with the LABS beacon turned on. This additional unknown changes how well the horizontal position can be estimated. In FIG. 7 the HDOP map for the aircraft fleet is presented, which is somewhat deteriorated from FIG. 6. For the aircraft fleet the horizontal position can be predicted to within three meters two sigma throughout the airport region.

For aircraft still in the air it is desirable to track their altitude as well, but to do so would require that some receivers 12 be positioned well out of the horizontal plane. Referring back to the receiver site diagram in FIG. 5, four receivers 12 are on three meter masts off the corners of the airport and one receiver is at fifteen meters on a tower. This is a relatively unobtrusive installation and provides good horizontal position accuracy throughout the airport region. We may need substantially higher antenna masts to get good vertical dilution of precision (VDOP) from the LABS. It is really a two-dimensional system. Fortunately horizontal accuracy is not sacrificed when an aircraft is still in the air. The high VDOP is advantageous in that sense, a 100 meter altitude would map back to less than a meter of horizontal error throughout most of the airport region.

In one embodiment of the invention, the LABS has a capacity to support one thousand beacons 14 operating simultaneously in the same band, maintain an average one second position update interval, and miss less than one in one thousand fix attempts. The

beacons 14 are transmitting at random times and the transmissions will collide. FIG. 8 is the result of the simulation for varying code rates. Figure 8 shows that the collision rate can be kept below one in one thousand for a code rate of approximately 3.6 MHz, which serves as a baseline.

There are many potential applications of the LABS. The defining conditions are the desire to locate objects in a fixed area of interest with low cost, low power beacons. In applications where there is significant blockage and foliage the LABS has an advantage over GPS based systems. LABS can be used indoors. The LABS beacon may be pager sized and easily carried by personnel. One or more bits can be added to the waveform to indicate additional information from the beacon, particularly an emergency of some kind. Some applications of the invention are: locating skiers in a ski area, locating people and equipment in warehouses and factories, locating key personnel in an airport, locating customers or key personnel in an amusement park.

Another class of applications for the LABS are situations applications where the assets or personnel to be tracked are going to be operating in a region for some period of time, but not permanently. In this case the area of interest is identified and portable receivers 12 are positioned around the perimeter. The receiver's self-survey using GPS or DGPS. The LABS transponders then work in the usual fashion. This system can support law enforcement agencies, fire departments, construction crews and other operations where personnel and equipment move through buildings and in an urban canyon environment where GPS coverage cannot be relied upon. For firefighters and law enforcement officers in particular, a timely picture of the location of all team members in a building can be crucial to saving lives.

It will be apparent from the foregoing that, while particular forms of the invention have been illustrated and described, various modifications can be made without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. A system for determining the location of a plurality of objects within a local area, said system comprising:

for each object, a beacon carried by the object for transmitting a beacon signal at a random time;

at least three receivers located within the local areas for receiving each beacon signal and recording the time of arrival of each beacon signal with a local clock; and

a base station for receiving data indicative of the time of arrival and processing the difference in the time of arrival of the beacon signal at each of the receivers to determine the location of the beacon within the local area.

2. The system of claim 1 wherein each beacon transmits its beacon signal over the same carrier frequency.

3. The system of claim 2 wherein multiple beacon signals are carried over the same carrier frequency through the use of at least one of time-division multiplexing and code-division multiplexing.

4. The system of claim 3 wherein each receiver separates the multiple beacon signals by at least one of time-division multiplexing and code-division multiplexing.

5. The system of claim 1 wherein the beacon signal comprises a beacon code burst comprising a family code and a beacon-identification code.

6. The system of claim 5 wherein the family code is added to the beacon signal by phase shift keying.

7. The system of claim 5 wherein each receiver correlates a replica of the family code with the family code of the received beacon signal to detect the arrival of a beacon signal.

8. The system of claim 1 wherein each receiver comprises a GPS receiver and the receiver local clocks are synchronized by transferring GPS time to the local clocks.

9. The system of claim 1 wherein each receiver comprises a GPS receiver and the receiver local clocks are synchronized using differential GPS processing with a common set of corrections supplied over the data cable from the base station.

10. The system of claim 1 wherein the base station comprises a single master clock and the receiver local clocks are synchronized using send and reply correction messages from the master clock to observe and compute the delay time on each data cable between the base station and the receiver.

11. The system of claim 1 wherein the data received by the base station from the receivers further comprises an beacon-identification code and beacon signal quality indicators for the beacon signal received.

12. The system of claim 1 wherein at least one of the objects further comprises a DGPS receiver and the beacon signal transmitted by the at least one object includes position information provided by the DGPS along with the family code and the beacon-identification code.

13. The system of claim 1 wherein the plurality of objects comprise different types of objects, a different family code is assigned to each type of object and the family codes are separated in the receivers using code-division multiplexing.

14. Within a local area having a plurality of objects, a method of determining the location of the plurality of objects, said method comprising the steps of:

from each object, transmitting a beacon signal at a random time;

receiving each beacon signal at at least three receivers located within the local areas;

at each receiver, recording the time of arrival of each beacon signal with a local clock; and

processing the difference in the time of arrival of the beacon signal at each of the receivers to determine the location of the beacon within the local area.

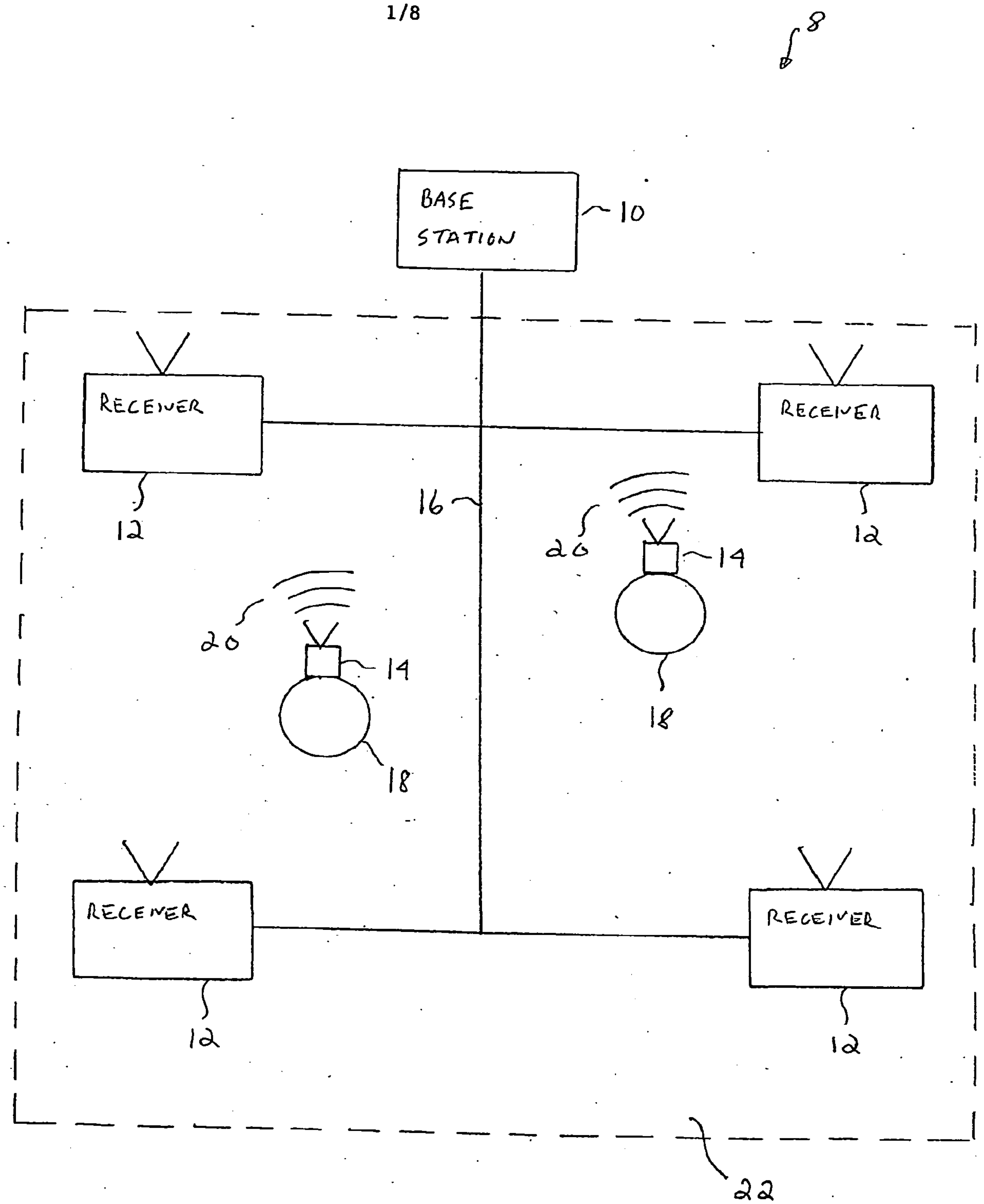

8
BASE STATION
10
RECEIVER
RECEIVER
RECEIVER
RECEIVER
12
12
12
12
16
20
20
14
14
18
18
22

FIG. 1

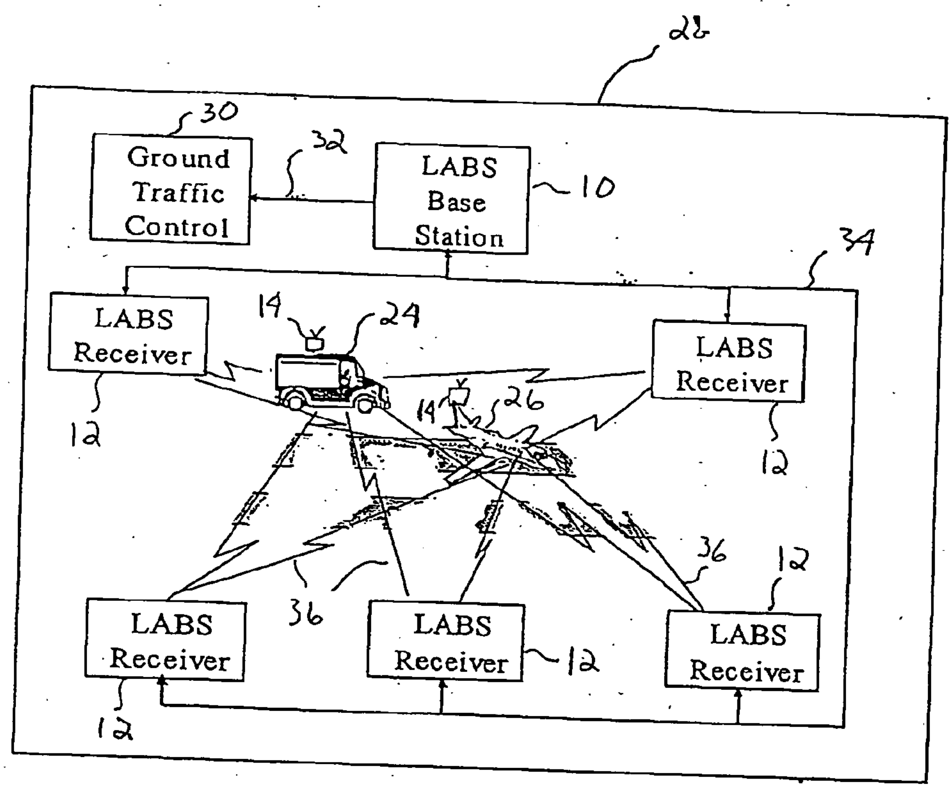

28
30
Ground
Traffic
Control
32
LABS
Base
Station
10
34
LABS
Receiver
14
24
LABS
Receiver
12
14
26
12
36
12
LABS
Receiver
36
LABS
Receiver
12
LABS
Receiver
12

FIG. 2

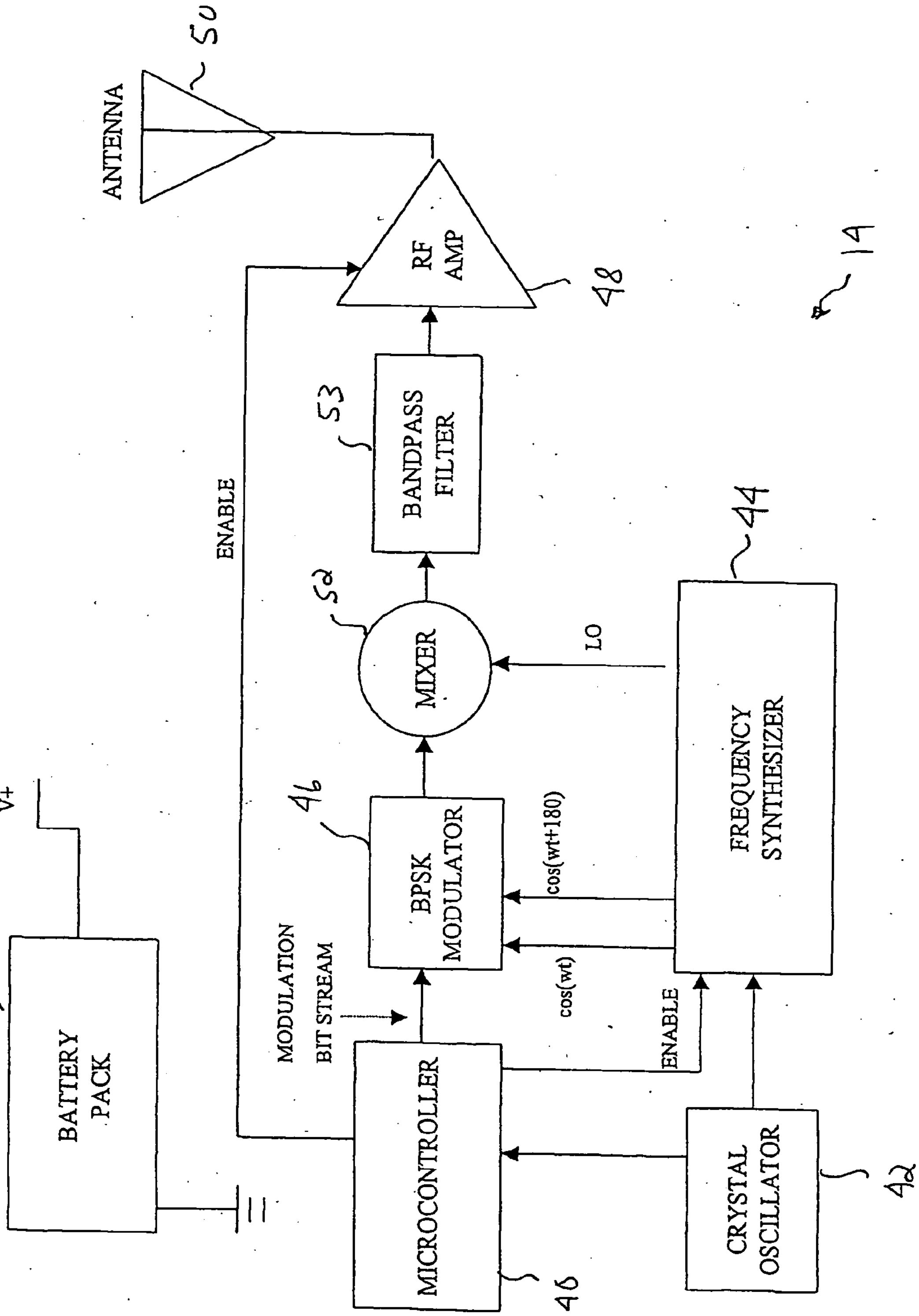

ANTENNA
50
RF AMP
48
14
BANDPASS FILTER
53
ENABLE
MIXER
52
LO
FREQUENCY SYNTHESIZER
44
BPSK MODULATOR
46
cos(wt+180)
cos(wt)
MODULATION BIT STREAM
ENABLE
V+
BATTERY PACK
38
MICROCONTROLLER
40
CRYSTAL OSCILLATOR
42

FIG. 3

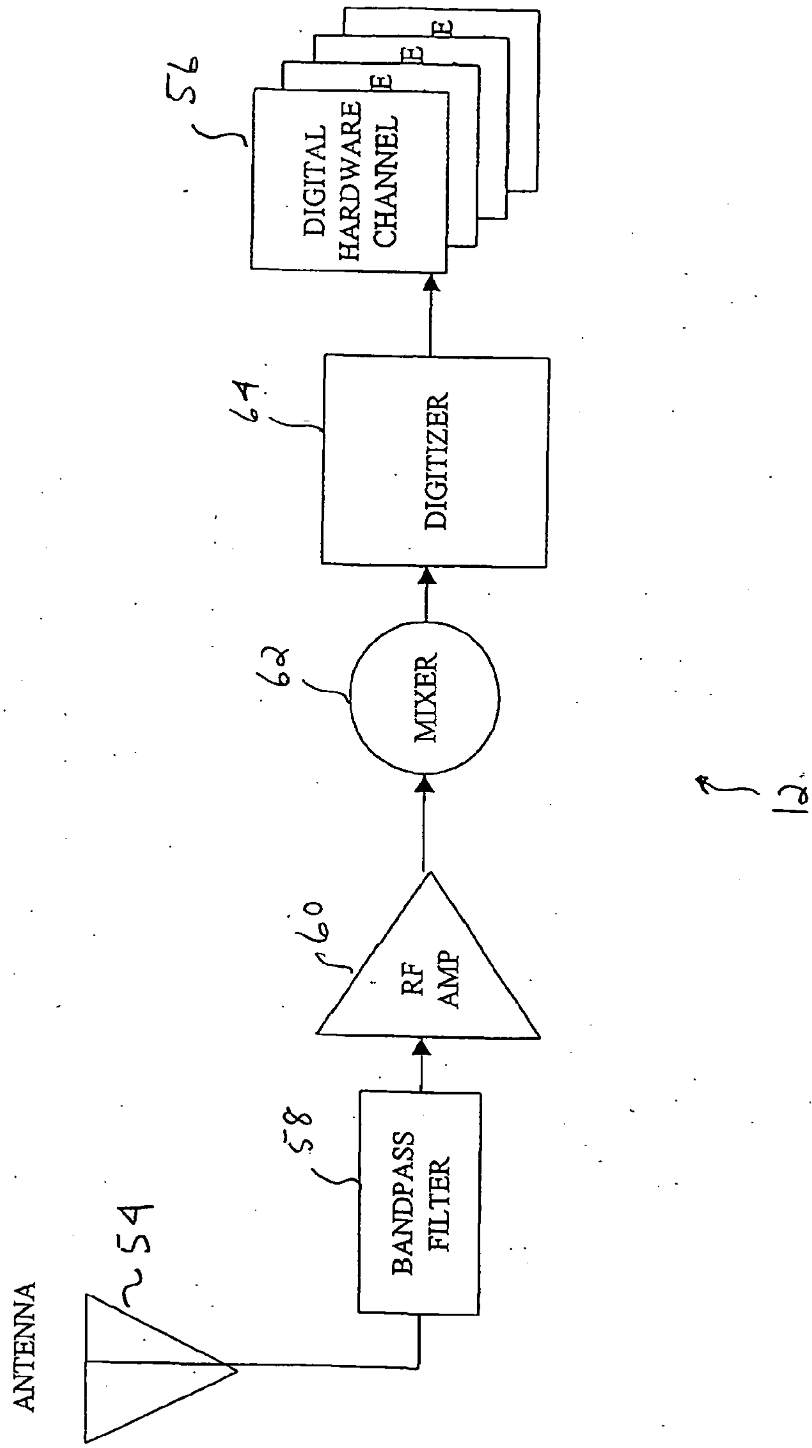

ANTENNA
54
BANDPASS FILTER
58
RF AMP
60
MIXER
62
DIGITIZER
64
DIGITAL HARDWARE CHANNEL
56
12

FIG. 4

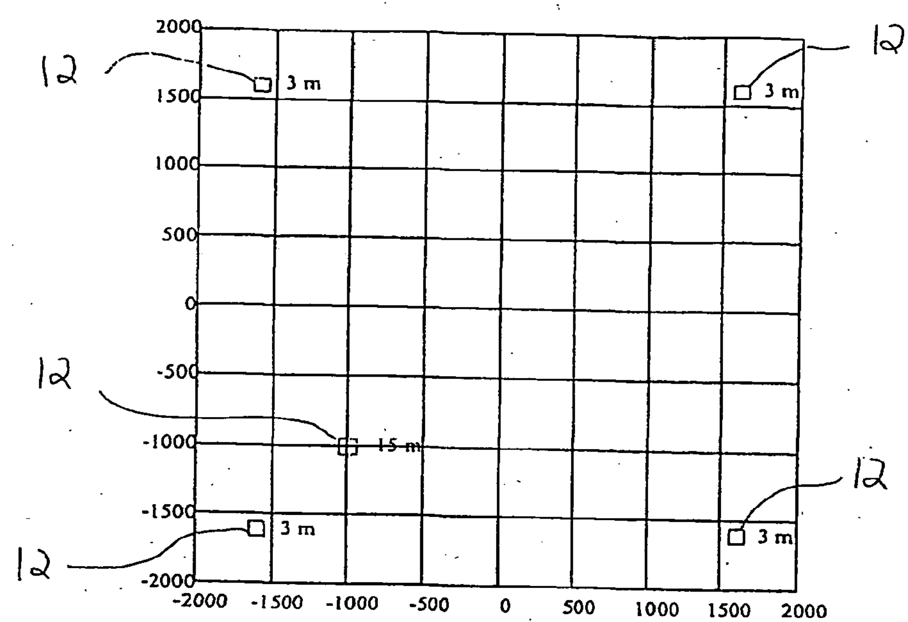

12
12
12
12
12
3 m
3 m
15 m
3 m
3 m
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2000
-1500
-1000
-500
0
500
1000
1500
2000

FIG. 5

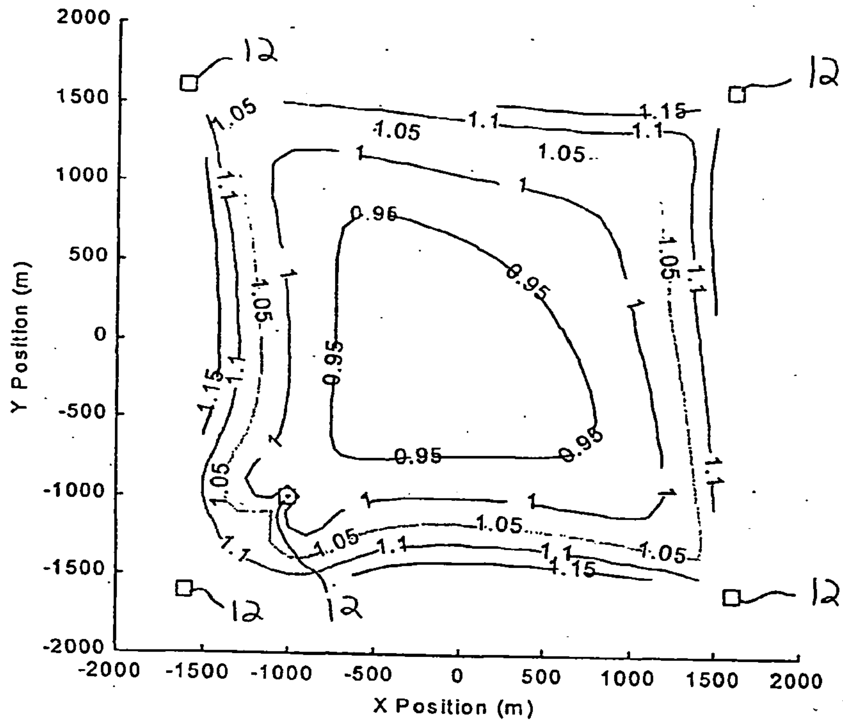

2000
1500
1000
500
0
-500
-1000
-1500
-2000
Y Position (m)
-2000
-1500
-1000
-500
0
500
1000
1500
2000
X Position (m)
12
12
12
12
12
1.05
1.1
1.15
1
0.95

FIG. 6

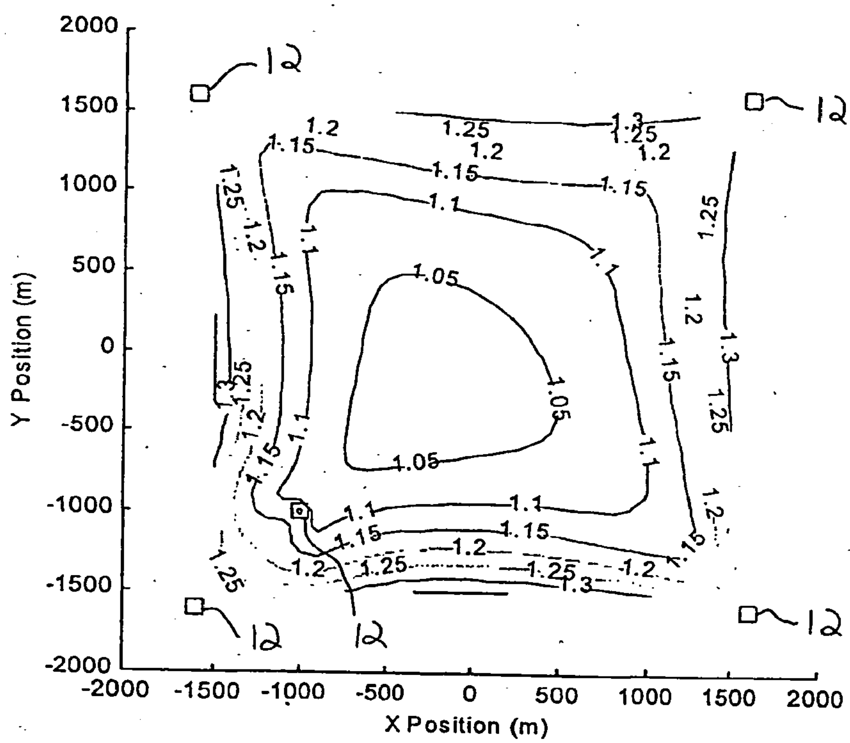


FIG. 7

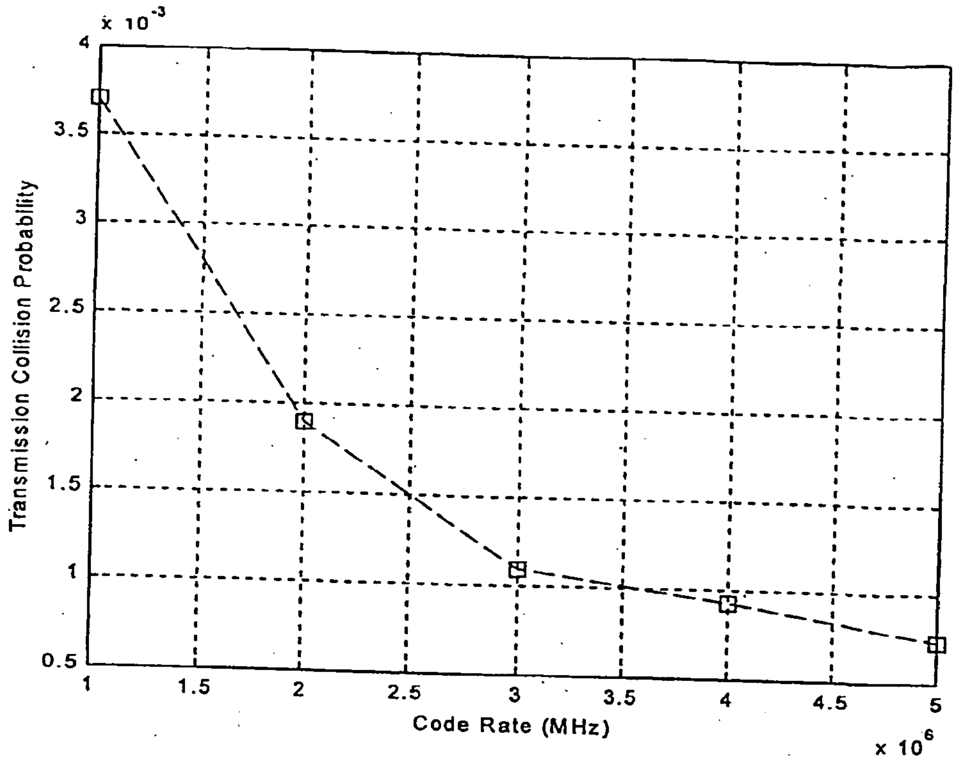

x 10^-3
4
3.5
3
2.5
2
1.5
1
0.5
Transmission Collision Probability
1
1.5
2
2.5
3
3.5
4
4.5
5
Code Rate (MHz)
x 10^6

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/20066

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : G01S 1/24, 3/02
US CL : 342/387, 465
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 342/387, 465, 386, 457

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
IEEExplore: TDOA and CDMA; TDOA and GPS; radiolocation and cdma

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 5,327,144 A, (STILP et al) 5 July 1994, 05.07.1994, see entire document.	1-4, 8, 10 and 14 --- 5-7, 9 and 11-13
X --- Y	US 5,859,613 A (OTTO) 12 January 1999 (12.01.1999), see entire document, particularly Fig. 1.	1-4, 8, 10, and 14 --- 5-7, 9, and 11-13
X	CAFFERY, James J. et al, "Overview of Radiolocation in CDMA Cellular Systems", IEEE Communications Magazine, April 1998, pages 40-41.	1-4, 8 and 14
Y	US 5,920,287 A (BELCHER et al) 06 July 1999 (06.07.1999), See Figure 1 particularly, entire document overall.	1-14
Y	US 3,714,573 A (GROSSMAN) 30 January 1973 (30.01.1973), see entire document.	1-14

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 August 2001 (27.08.2001)	24 OCT 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer Gregory C. Issing Telephone No. (703) 308-1113